

High Bandwidth Terahertz Communication Link

Final Report

For Period: 23 October 2012 – 27 February 2013

Contract Number: W31P4Q-13-P-0006

Document Number: 8479-R

Contract Awarded Through:
US Army Contracting Command-Redstone

Topic Number SBIR A11-079

Prepared for:

Henry O. Everitt, Ph.D.
Senior Research Scientist (ST)
Department of the Army
Weapons Sciences Directorate
RDMR-WS/Dr. Everitt
Research, Development, and Engineering Center
Building 7804, Room 248 Redstone Arsenal, AL 35898-5000
P: (256) 876-1623 F: (256) 876-4759
E: henry.o.everitt@us.army.mil

Prepared by:

Trex Enterprises Corporation
10455 Pacific Center Court
San Diego, CA 92121-4339
(858) 646-5300

Technical Point of Contact:

Richard Chedester, Principal Investigator
P: (413) 247-9440 (Ext. 10) F: (413) 247-9439
E: rchedester@trexenterprises.com

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE MAR 2013		2. REPORT TYPE		3. DATES COVERED 00-00-2013 to 00-00-2013	
4. TITLE AND SUBTITLE High Bandwidth Terahertz Communication Link				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Trex Enterprises Corporation,10455 Pacific Center Court,San Diego,CA,92121				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washing Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</small> PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS					
1. REPORT DATE (DD-MM-YYYY) 27-02-2013		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 23Oct2012 – 27Feb2013	
4. TITLE AND SUBTITLE High Bandwidth Terahertz Communication Link Phase I Option				5a. CONTRACT NUMBER W31P4Q-13-P-0006	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Richard Chedester				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Trex Enterprises Corporation 10455 Pacific Center Court San Diego, CA 92121-4339				8. PERFORMING ORGANIZATION REPORT NUMBER 8479-R	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Army Contracting Command-Redstone CCAM-RD-A Redstone Arsenal, AL 35898-5280				10. SPONSOR/MONITOR'S ACRONYM(S) CCAM-RD-A	
				11. SPONSOR/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT Distribution Statement A: Approved for public release; distribution is unlimited. Date of Determination: 26 SEP 12.					
13. SUPPLEMENTARY NOTES None					
14. ABSTRACT During Phase one Option period, Trex performed extensive research into THz-range passive and active component that will be required make the Phase two hardware. The design of a custom MMIC was completed so it could be ordered processed with the once a year Pizza mask process at UMS. These parts are expected to arrive later this year when the Phase 2 contract is awarded and results in a significant cost saving in the development of a custom mixer. In addition the source pricing for the MMIC amplifier was also completed. This process took much longer than expected and this will speed up the process of betting parts during the second phase of the program. In addition direction of the overall mechanical configuration was outlined to speed up the process for the detailed design that will be undertaken in the next phase of the program. The radios will be designed to communicate in a half-duplex at 3 Gbps and full duplex using TDD mode at 1 Gbps data rate. The details of the TDD mode being much more complex were looked into in more detail during the option phase.					
15. SUBJECT TERMS High Bandwidth, Terahertz Communication, millimeter-wave Gigabit, transceiver, secure communications.					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 13	19a. NAME OF RESPONSIBLE PERSON Henry Everitt
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) (256) 876-1623

This document is a scheduled report for the Phase I Option development of High Bandwidth Terahertz Communication Link for communication in the 165-178 GHz frequency band at Gigabit data rates (CCAM-RD-A contract W31P4Q-13-P-0006).

CONTENT

- 1) Proposed design of Time Division Duplex (TDD) Terahertz radio**
- 2) Phase I Option development**
 - 2.1 Assess availability of sub-THz components and procure long lead parts**
 - 2.2 Perform detail mechanical design of the radios**
 - 2.3 Preliminary design of the digital data buffering circuit for TDD operation**
- 3) Commercial development of THz radios through Trex Loea business**
- 4) Attachments**

1) Proposed design of Time Division Duplex (TDD) Terahertz radio

In Phase I Trex proposed to design and demonstrate a prototype of a high bandwidth THz Radio reconfigurable for operation at 3 Gbps data rate for unidirectional links and 1 Gbps TDD bi-directional links. The radio transceiver shown in Figure 1 will have the flexibility to switch between the two modes by the operator request. All of the necessary system components are commercially available and many of the subsystem blocks shown are taken from existing product lines of Trex/Loea E-band millimeter-wave Gigabit radios. These items, shown in yellow, can be rapidly integrated into a compact package with minimized development cost to meet the needs of the current program.

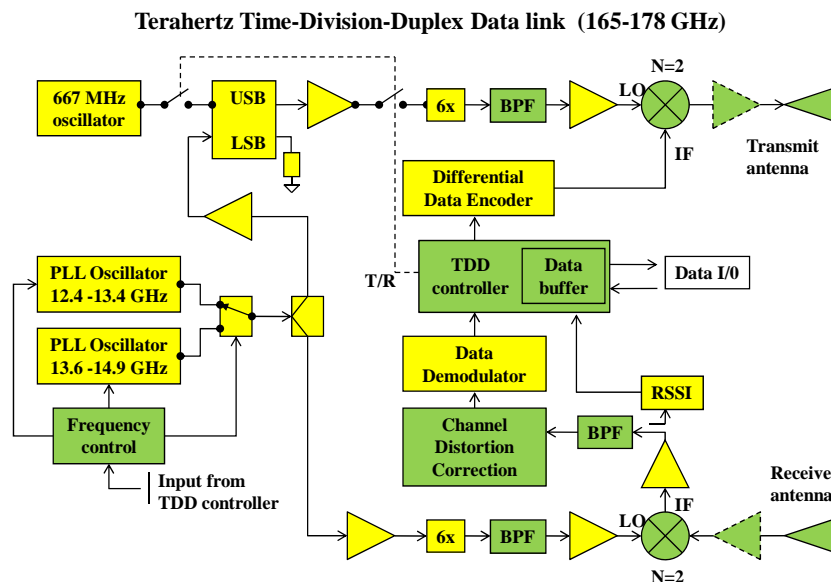


Figure 1. Block diagram for the frequency-agile THz TDD Radio Prototype

The carrier frequency of the transceiver can be set at any frequency between 165 GHz and 178 GHz. In order to establish a link, the transmitters and receivers will initially implement a handshaking protocol at 165 GHz where atmospheric attenuation is the lowest. This allows any THz Radio that wants to communicate with any cooperative THz Radio, to configure the receive unit to accept the data. Once the two units have established contact, the embedded firmware will negotiate their operating frequency, which will maintain the shortest possible link range. For the remainder of the transaction, the data will be passed in one or both directions at Gigabit or higher rates based on a push-to-talk protocol.

The above configuration allows the radio to have large frequency coverage and to be rapidly tunable. This is crucial for the link to take advantage of prevailing atmospheric absorption characteristics for maximum covertness.

For ranges greater than 200 meters, the transmit and receive signals have to be amplified to ensure there is sufficient power budget for longer range communication. During Phase I and the Option effort, Trex has performed extensive research of potential THz amplifier vendors considering cost, size, weight and power (SWaP) requirements for the battery operated radios described in the proposal. A THz transmit power amplifier (PA) and/or a THz receive low noise amplifier (LNA) are taken to be add-as-required components for each specific application. In Figure 1, these optional amplifier modules are shown using dashed outlines next to the transmit and receive antennas.

2) Phase I Option development

Phase 1 proposal included an Option with the following tasks:

- Assess Sub-THz component availability
- Order long lead parts
- Detail mechanical design
- Reporting

2.1) Assess availability of sub-THz components

During Phase I and Option period, Trex performed extensive research into THz-range passive and active component options for the 165-178 GHz frequency range. Although THz-range components can be procured from vendors such as Virginia Diodes and Northrop Grumman for low conversion loss THz mixers, and amplifiers, these vendors do not offer monolithic microwave integrated circuits (MMIC.) They primarily sell connectorized modules with waveguide input and output ports and their prices are high. Besides the cost, such modular components put undesirable constrictions on the SWaP requirements of the radio design. Trex has a fully equipped facility and the know-how capabilities for assembling and testing high-complexity millimeter and sub-millimeter-wave circuits using MMIC components. Trex also has experience with designing and modeling such MMIC circuits which can be then fabricated by a third party foundry. Therefore, our component research has been focused on identifying vendors of the THz frequency range MMIC amplifiers and mixers and establishing business relationships which will allow small quantity fabrication of such components at an affordable cost.

For the THz up-and-down-frequency converting mixers, Trex has chosen United Monolithic Semiconductors (UMS)-GAAS foundry in France to fabricate Qty 15 Trex-designed mixer MMICs for a very favorable total cost of \$5,550 (as shown in the Attachment A.) The mixers

have been ordered as long lead items using the Phase I Option project funding. These second harmonic mixers have been designed for the center frequency of 170 GHz, and will be used in both the receiver and transmitter for the up-and-down-conversion of the 165-178 GHz signals to or from the intermediate frequency (IF) range. The mixers will be driven by local oscillators (LO) similar to the ones used in Trex/Loea millimeter-wave radios. Design layout of the MMIC is shown in Figure.2.

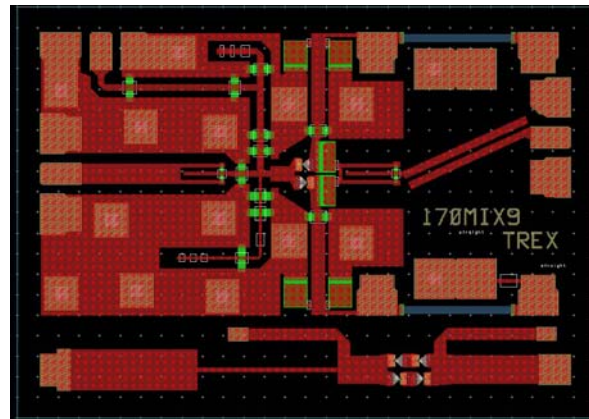


Figure 2. Layout of the 170MIX9 THz MMIC mixer designed by Trex

In order to procure sub-THz amplifiers, Trex has established a business relationship with Fraunhofer Institute for Applied Solid State Physics in Germany, and obtained a formal quote for Qty 4, medium power THz amplifier MMICs. The quote is shown as the Attachment B. The amplifiers have a design gain of 20 dB and compressed power output of approximately 2 mW, which would be sufficient to close a 3 Gbps link up to 400 meters in clear weather. The S-parameter characteristics of the MMIC amplifier are shown in Figure. 3.

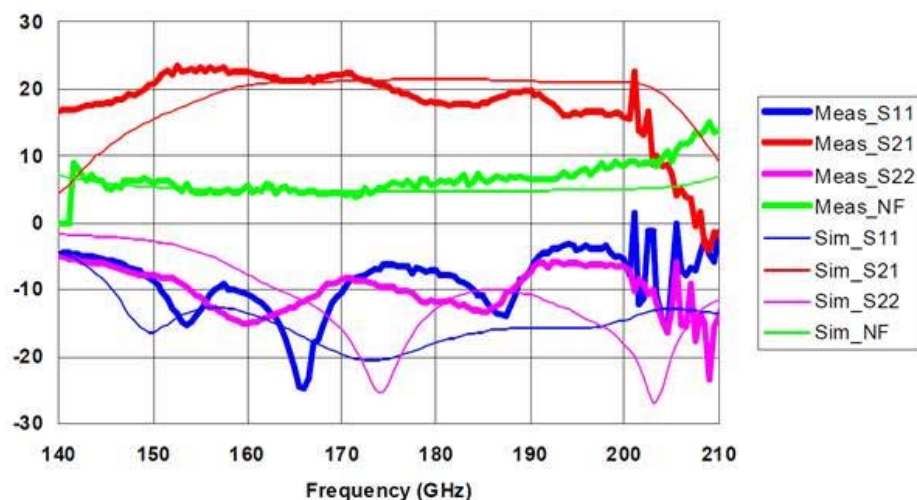


Figure 3. S-params of Fraunhofer MMIC Amplifier

2.2) Perform detail mechanical design of the radios

During Phase 1 option period Trex elaborated on details of the mechanical components and the overall layout of the proposed THz radio. The assembly drawing of the THz transceiver is shown in Figure 4. The transmit and receive module will incorporate all THz and IF components and will provide digital data input for the transmitter and digital data output for the receiver via SMA connectors. The THz transmit and receive horns will be placed in the focus of the rectangular dielectric lenses which will determine the size of the THz antenna aperture and, ultimately, the angular width and shape of the THz beams. The lenses can be customized to optimize the beam configuration for range and angular field of view (FOV.) The size of the antenna aperture can be varied by using optional external diaphragm attachments or by installing an additional pair of lenses between the feedhorns and the aperture antennas. The digital signals will be processed by the system controller and memory buffer, whose layout will be discussed later in this report. The THz module design is illustrated by the mechanical drawing of the transmit module shown in Figure 5. A split block metal housing of the module will enclose a waveguide channel containing both active/passive MMIC devices, filtering and interconnect components. An assembly diagram of the transmit module (Figure 6) also shows bias boards providing voltages to the components and connections to the system controls. Trex has also designed a matched probe transition (Figure 7) between the planar receive / transmit circuits and the waveguide ports of the antenna feedhorns.

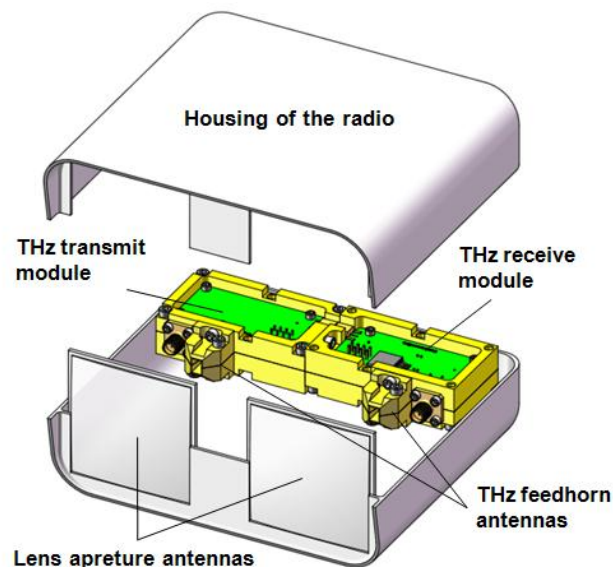


Figure 4. Mechanical design of the THz radio assembly

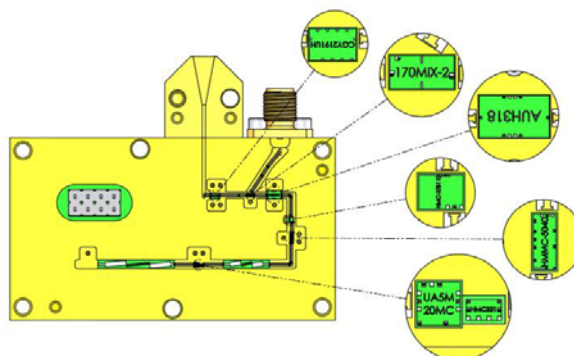


Figure 5. Mechanical design of the THz transmit module and layout of the MMIC components

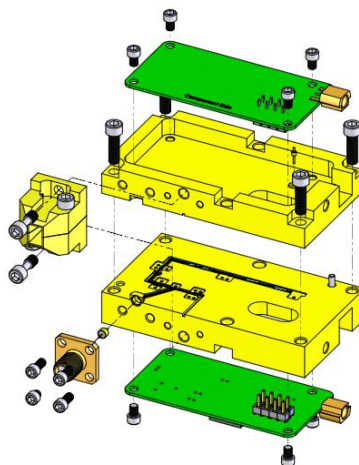


Figure 6. Mechanical assembly diagram of the THz transmit module

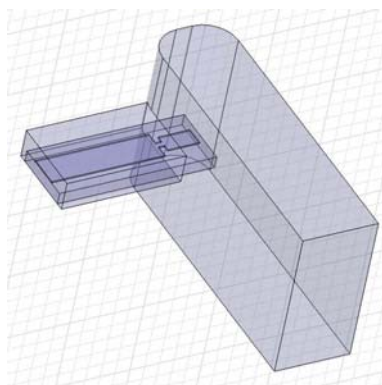


Figure 7. Design of the matched planar to waveguide probe transition for THz feedhorn antennas

2.3) Preliminary design of the digital data buffering circuit for TDD operation

The proposed radio uses same THz frequency band to transmit and receive data, which precludes it from transmitting and receiving data simultaneously by the same transceiver module. Uni-directional communication at 3 Gbps data rate is not affected by this constriction, but the bi-directional link will require a time division TDD approach, where transmitter and receiver in each module are not allowed to operate over the same time period. The radios will be designed to communicate in the TDD mode at 1 Gbps data rate by buffering the transmit data during the receive interval. The transmission rate will be accelerated to 3 Gbps during the transmit interval. The accelerated transmission will allow it to clear the buffer memory and to give additional time for a new reception cycle. In TDD mode the transmit-receive switching of the modules will be coordinated by the control module. The critical part of the system is the large size and high speed memory buffer as well as the data rate adapter circuit. Trex will design this circuit using a high performance Xilinx or Altera Field Programmable Gate Arrays (FPGA) using multi-gigabit transceiver technology. The FPGA's will use high speed serializer-deserializers as well as 8b/10b or 64b/66b encoding options to prevent any DC level drift. On the receiver end, the clock and data recovery circuits will extract the clock from the data stream, and align the data in words. The parallel FPGA input-output data will be clocked in using 16 bit or wider parallel interface at 300 MHz, which will be directed to and from external memory buffers. Trex has already implemented similar circuits at 2 Gbps data rates for its >200 Megapixel digital camera product. A functional diagram of the digital buffer and data rate adapter circuits are shown in Figure 8. The final implementation of the circuits will be decided based on whether serializing-deserializing of the data will be done within the FPGA or by the dedicated external components, and whether the memory buffers will use external SRAM or FPGA internal memory. These decisions will be made by analyzing the power consumption of alternate circuit configurations. The diagram in Figure 8 shows that the data is extensively serialized-deserialized in order to allow real-time processing within FPGA whose clock speed is lower than the data rate. Figure 8 shows a case where to-be-transmitted-in-the-next-cycle data in Transceiver 1 is buffered at 1 Gbps in the SRAM1 memory, while a previously accumulated block of the data is transmitted at 3 Gbps. Transceiver 2 receives data from Transceiver 1 at 3 Gbps and fills SRAM2. During this time interval, the transmit channel of the Transceiver 2 is disabled, and the receive channel is connected to the feedhorn antenna. At the same time, the Transmit 1 channel is enabled, and sends data through the antenna at 3 Gbps rate, emptying the buffer three times faster than it is filled by the 1 Gbps input data. Its receive channel is disconnected from the antenna, and sends accumulated data from the buffer, to the output at a 1 Gbps rate. Once the Transceiver 1 transmits the previously accumulated block of the data, the transceivers swap their roles, where Transceiver 2 becomes the transmitter, and Transceiver 1 becomes the receiver. The timing diagram shown in Figure 9 further illustrates this highly synchronized transmit-receive process.

Block diagram of the THz radio operating in 1 Gbps TDD mode

- Shown is Tx/Rx switch position for a cycle of data transfer from Transceiver 1 to Transceiver 2 at an accelerated rate of 3 Gbps

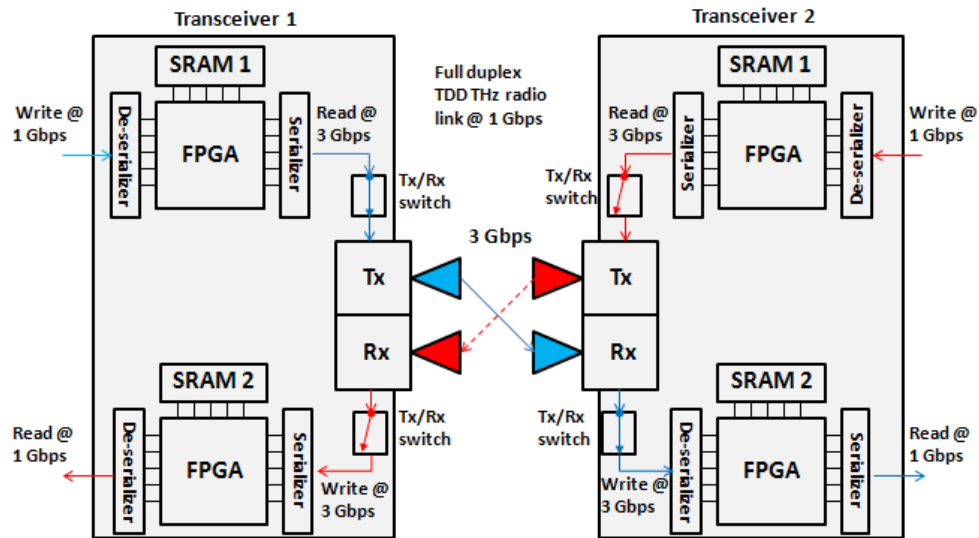


Figure 8. Design of the data buffer and the data rate adapter circuit for the THz radio operating in the 1 Gbps TDD mode.

Data transfer timing diagram of the THz link in 1Gbps TDD mode

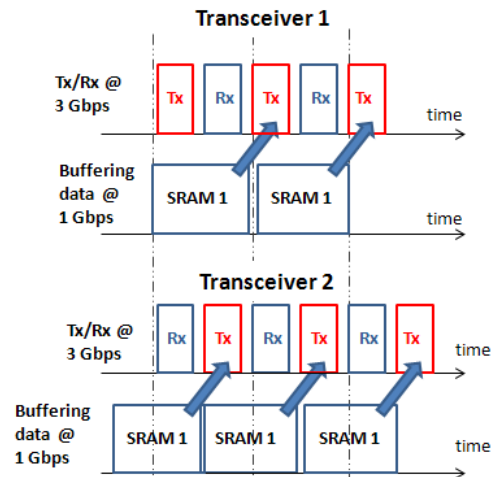


Figure 9. Timing diagram of the synchronized 3 Gbps transmit, receive and 1 Gbps data buffering cycles of the bi-directional THz TDD radio at 1 Gbps data rate

3) Commercial development of THz radios through Trex Loea business

Trex plans to introduce the proposed Gigabit Terahertz radio into its Loea Corp. millimeter-wave commercial product portfolio after the development passes through its principal design, cost reduction and demonstration phases. The greatest marketing advantage of this product is its significantly smaller footprint compared to existing systems having similar capacity and feasibility of ultra-high data rates with low-order modulation methods. Trex sees high cost as the main obstacle to successful commercialization of this product, primarily due to the cost of the THz amplifier components. To make this new product competitive, Trex needs to gain access to low cost THz MMIC amplifiers and other components by developing business relationships with academic and industrial partners providing foundry design and fabrication services using advanced InP pHEMT process both domestically and abroad.

Trex/Loea was the company that petitioned the FCC in 2001 to open up the E-Band space for point-to-point communications, resulting in the 2003 Rulemaking that made the 71-76 and 81-86 GHz channels available for these applications today. Thus Trex has experience in this policy making arena, and in commercialization of radio technology. Today Loea Communications Corporation is one of the three leading companies in the world for production of multi-Gbps radios in the E-Band spectrum, and is poised to add licensed and unlicensed radios in the 160-180 GHz band, and eventually license-free radios in the > 300 GHz band, to its product portfolio.

4) Attachments

Attachment A

UMS-GAAS purchase order confirmation for fabrication of Qty 3 of the MMIC wafer reticles with a projected yield of 15 qualified mixer devices based on the Trex design

united monolithic semiconductors
Quality and Environmental Management System
ISO 9001 - ISO 14001 & ISO 16185/49
CENTRE EXPÉDITEUR DE CE DOCUMENT :
Bâtiment Charmille - Parc Silic de Villebon-Courtabœuf
10 avenue du Québec - 91140 Villebon-sur-Yvette - France
ADRESSE POSTALE : 10 avenue du Québec - Silic 521
91946 Courtabœuf Cedex - France
Service Commercial : TÉL. : +33 (0)1 69 86 32 00 / TÉLÉCOPIE : +33 (0)1 69 86 34 34
Service Comptabilité : TÉL. : +33 (0)1 69 86 32 87 / TÉLÉCOPIE : +33 (0)1 69 86 34 00
Our VAT Identifier FR 69383144102



ORDER ACKNOWLEDGEMENT

Delivered to
TREX ENTERPRISES CORPORATION
164 WEST STREET
WEST HATFIELD
MA 01088
UNITED STATES OF AMERICA

Ordered by
TREX ENTERPRISES CORPORATION
10455 Pacific Center Court
SAN DIEGO, CA
9212164339
UNITED STATES OF AMERICA

Our ref.	23329	From	28/11/2012	Customer	2009467
Your ref.	59933	From	28/11/2012		
Payments Terms	30 DAYS NET				
Incoterm	DAP DELIVERY AT CUSTOMER PLACE				

Order Line	Reference	Delivery dd/mm/yy	Unit	Qty	Unit Price E-VAT	Amount	Currency
10	BE Activity & Chips Delivery Mask BILBO Process BES WP10M_FA	25/02/13	UN	3,00	1.850,00	5.550,00	USD

Attachment B

Formal quote for fabrication of Qty 4 medium power MMIC amplifiers for the 165-178 GHz radios

Fraunhofer IAF | Tullastraße 72 | 79108 Freiburg

Trex Enterprises
Mr Richard Chedester
164 West Street
W. HATFIELD, MA 01088
USA



Fraunhofer Institute for
Applied Solid State Physics IAF

Director
Prof. Dr. rer. nat. Oliver Ambacher

Tullastraße 72
79108 Freiburg

Beatrice Scherer
Phone + 49 761 5159-415 | Fax + 71-415
beatrice.scherer@iaf.fraunhofer.de
www.iaf.fraunhofer.de

Freiburg, December 12, 2012

Dear Mr Chedester

Quotation 1212508
IAF-Project 385034

Development and Delivery of Low-Noise Amplifiers

Based on our enclosed »General Terms and Conditions for Research and Development contracted to Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.« we are pleased to offer the following:

Pos.	Description	Quantity	Unit price €	Total price €
01	Low-Noise Amplifier LNA 180 GHz	4	1,050.00	4,200.00
	VAT added if applicable			4,200.00

The export of these goods is subject to the restrictions of the Federal Republic of Germany and the EU
Commodity Code: 85423300, Exportlist No (AL): 3A001 b 2 f)